

Contradicting effective mass scalings within the Skyrme energy density functional method

W. Satuła,^{1,2,*} R. A. Wyss,^{2,†} and M. Zalewski^{1,‡}

¹*Institute of Theoretical Physics, University of Warsaw, ul. Hoża 69, 00-681 Warsaw, Poland*

²*KTH (Royal Institute of Technology),
AlbaNova University Center, 106 91 Stockholm, Sweden
(Dated: February 25, 2008)*

The problem of the effective mass scaling in the single particle spectra calculated within the Skyrme energy density functional (EDF) method is studied. It is demonstrated that for specific pairs of orbitals the commonly anticipated isoscalar effective mass (m^*) scaling of the single-particle level splittings is almost canceled by an implicit m^* -scaling due to other parameters in the Skyrme EDF. This holds in particular for an indirect m^* -scaling of the two-body spin-orbit strength making the theory essentially unpredictable with respect to single particle energies. It is argued that this unphysical property of the Skyrme EDF is a mere consequence of the strategies and datasets used to fit these functionals. The inclusion of certain single-particle spin-orbit splittings to fit the two-body spin-orbit and the tensor interaction strengths reinstates the conventional m^* -scaling and improves the performance of the Skyrme EDF.

PACS numbers: 21.10.Hw, 21.10.Pc, 21.60.Cs, 21.60.Jz

Fundamental excitations in atomic nuclei are often characterized in terms of single particle and collective excitations. A successful nuclear theory is required to account for both kinds at a qualitative *and* quantitative level. The effective nuclear energy density functionals (EDF) irrespectively of their variants including local (Skyrme), non-local (Gogny) or relativistic mean-field (RMF) have developed toward high accuracy in recent years, both with respect to bulk properties and predictions of single particle properties[1]. Still, on a quantitative level, properties of single particle states are often better described by means of simple potentials like the Nilsson or Woods-Saxon. This is highly unsatisfactory, since one expects a full fledged EDF to describe nuclear properties at a level of accuracy superior to that of simple potentials. The uncertainty of present EDF with respect to nuclear properties has its roots in the fitting procedure of its parameters as well as the non local terms in the interaction.

The EDF's are conventionally adjusted to reproduce ground-state bulk nuclear properties, see e.g. Ref.[2]. The datasets used to fit their parameters are dominated by nuclear data extrapolated to the thermodynamic limit and by nuclear binding energies in selected doubly magic nuclei. These fitting procedures are known to impair basic building blocks of these theoretical models, in particular single-particle (s.p.) energies. The physical relevance of s.p. energies provided by self-consistent mean-field (MF) approaches based on the EDFs or effective interactions is continuously contested. The debate has its roots in the non-locality of these approaches result-

ing in a low isoscalar effective mass $\frac{m^*}{m} \approx 0.8$ [3] which in turn scales the s.p. level density g in the vicinity of the Fermi energy ε_F according to the simple rule: $g(\varepsilon_F) \rightarrow \frac{m}{m^*}g(\varepsilon_F)$. This simple rule applies strictly to homogeneous nuclear matter only. In finite nuclei the effective mass depends on \mathbf{r} and the $g(\varepsilon_F) \rightarrow \frac{m}{m^*}g(\varepsilon_F)$ scaling should be considered as an idealization. The effective mass scaling leads to a dichotomous and in fact highly uncomfortable situation. Indeed, in spite of the fact that it makes all applications of the self-consistent MF methods to low-lying nuclear excitations rather dubious such calculations are carried out routinely and published often without even a word of comment or justification.

The aim of this Letter is to demonstrate that the problem of the effective mass scaling within the *effective theory* is far more intricate than anticipated. It turns out that the effective mass dependence of the calculated single particle spectrum can depend on the structure of the EDF, on the strategies employed when adjusting the interactions and upon the choice of dataset used in these fits. We will demonstrate first that conventional functionals which are, as discussed above, fitted almost ultimately to bulk nuclear properties have an built in *implicit* effective mass scaling of certain coupling constants including in particular the two-body spin-orbit strength. For many modern parameterizations of the Skyrme force this mechanism is strong enough to cancel the effect of the s.p. level density scaling caused by the low effective mass with respect to the calculated specific particle-hole excitation. For example the $d_{3/2} - f_{7/2}$ splitting in $A \sim 44$ mass region [4] calculated using forces having effective masses ranging from $0.7 \leq \frac{m^*}{m} \leq 1$ yield similar result in spite of the expected effective mass dependence. In the next step we will show that this counterintuitive result is a mere consequence of the fitting strategies and that by shifting the attention from bulk to single-particle properties in the process of fitting of the nuclear EDF param-

*Electronic address: satula@fuw.edu.pl

†Electronic address: wyss@kth.se

‡Electronic address: zalewiak@fuw.edu.pl

eters one can both remove the artificial m^* -scaling from the two-body spin-orbit strength and reinstate the conventional and anticipated m^* -scaling in the calculated ph excitation energies.

All the calculations performed in this Letter are based on Skyrme-force inspired local EDF (SEDF) of the form:

$$\mathcal{H}(\mathbf{r}) = \sum_{t=0,1} (\mathcal{H}_t^{\text{even}}(\mathbf{r}) + \mathcal{H}_t^{\text{odd}}(\mathbf{r})) , \quad (1)$$

where

$$\mathcal{H}_t^{\text{even}} = C_t^\rho \rho_t^2 + C_t^{\Delta\rho} \rho_t \Delta\rho_t + C_t^\tau \rho_t \tau_t + C_t^J \mathbb{J}_t^2 + C_t^{\nabla J} \rho_t \nabla \cdot \mathbf{J}_t, \quad (2)$$

$$\mathcal{H}_t^{\text{odd}} = C_t^s \mathbf{s}_t^2 + C_t^{\Delta s} \mathbf{s}_t \cdot \Delta \mathbf{s}_t + C_t^T \mathbf{s}_t \cdot \mathbf{T}_t + C_t^{j_t^2} \mathbf{j}_t^2 + C_t^{\nabla j} \mathbf{s}_t \cdot (\nabla \times \mathbf{j}_t). \quad (3)$$

It depends on isoscalar $t = 0$ and isovector $t = 1$ time-even ρ_t , τ_t , and \mathbb{J}_t , and time-odd \mathbf{s}_t , \mathbf{T}_t , and \mathbf{j}_t , local densities for which we follow the convention introduced in Ref. [5], see also Refs. [6, 7] and references cited therein. All numerical results presented below were obtained using the HFODD code of Ref. [8] and the following set of the Skyrme forces: SLy4_L, SLy5_L [2], SIII_L [9], SkM_L^{*} [10], SkXc_L [11], MSk1_L [12], SkP_L [13], and SkO_L [14]. The subscript L indicates here that the original time-odd functional coupling constants C^s , $C^{\Delta s}$, and C^T were replaced in the calculations by the coupling constants reproducing the empirical Landau parameters in accordance to the prescription given in Refs. [4, 15].

In spite of the fact that we will concentrate here on the *implicit* m^* -scaling of certain functional coupling constants it should be mentioned that some of the SEDF parameters do scale or depend upon m^* explicitly. The *explicit* effective mass scaling is well established for the (i) C^s and C^T functional parameters through the fit to the empirical Landau parameters [4, 15] and (ii) for the isovectorial coupling constants C_1^ρ and C_1^τ through the fit to the empirical symmetry energy strength [16].

An almost ideal playground to investigate the impact of fitting procedures on the performance of the effective forces with respect to the ph related observables is offered by fully stretched $[f_{7/2}^n]_{I_{max}}$ and $[d_{3/2}^{-1} f_{7/2}^{n+1}]_{I_{max}}$ states in $N \neq Z$ nuclei in the $A \sim 44$ mass region where n denotes number of valence particles in the $f_{7/2}$ sub-shell [4]. In a series of publications [4, 17, 18, 19] we have demonstrated that these states represent one of the best examples of almost unperturbed single-particle motion and that the energy difference:

$$\Delta E = E([f_{7/2}^n]_{I_{max}}) - E([d_{3/2}^{-1} f_{7/2}^{n+1}]_{I_{max}}) \quad (4)$$

constitutes a very reliable probe of various properties of the EDF. In particular, it can be used to readjust the time-odd components C^s , $C^{\Delta s}$ and C^T to comply with

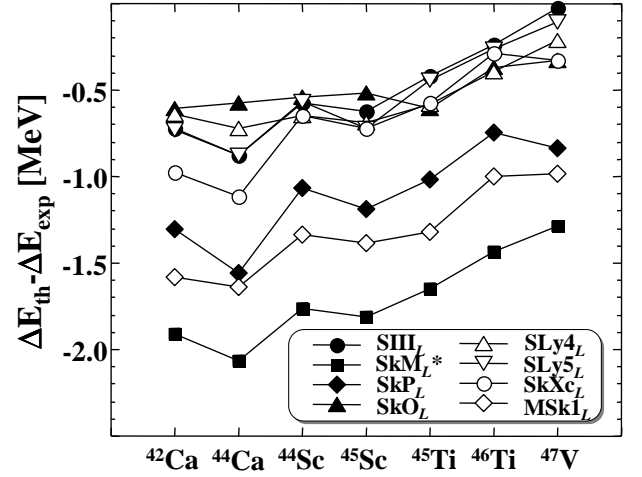


FIG. 1: The difference between theoretical and empirical values of the energy differences ΔE defined in Eq. (4). Calculations have been done using different popular parameterizations (see legend) of the Skyrme functionals with spin-dependent coupling constant readjusted to reproduce the empirical Landau parameters in accordance to Refs. [4, 15].

the empirical Landau parameters leading to an unification of the theoretical predictions for ΔE_{th} for various popular Skyrme parameterizations [4].

The calculated values of ΔE_{th} , see Fig. 1, show a striking and completely unexpected feature. The mean deviation of the theoretical predictions with respect to the empirical values is very similar for such forces like SLy4, SLy5 ($\frac{m^*}{m} \sim 0.7$), SIII ($\frac{m^*}{m} \sim 0.8$), SkO ($\frac{m^*}{m} \sim 0.9$) and SkXc ($\frac{m^*}{m} \sim 1.0$). In spite of the fact the effective masses differ by as much as 30%, we obtain for these parameterizations $\delta \bar{E} = \Delta \bar{E}_{th} - \Delta \bar{E}_{exp} \sim -550$ keV with a rms deviation of $\sigma \approx 70$ keV. This result is indeed extremely puzzling since the anticipated influence of a naive m^* -scaling with respect to a ph excitation energy of order of $\Delta \bar{E}_{exp} \approx 5.5$ MeV is, for the analyzed set of forces, estimated to be more than one order of magnitude larger, exceeding $\sigma \approx 1$ MeV.

Unexpectedly, the observable ΔE appears to be very robust. Indeed, the structural purity of the terminating states in the $A \sim 44$ mass region reveal a firmly established hierarchy of different physical contributions to that quantity and in turn allows to identify the physical source of the *cancellation* of the m^* -scaling in the functional. In Ref. [4] we established the hierarchy of three different components, the energy scale $\hbar\omega$, the strength of the spin-orbit (SO) and the ℓ^2 (surface) term using the Nilsson Hamiltonian. This schematic model clearly indicates the dominant influence of the mean SO potential on ΔE . This observation is neatly correlated with self-consistent SHF models, see the Appendix below where we give a numerical proof for the case of the Skyrme functionals. Indeed, the isoscalar strength of the Skyrme one-body SO potential emerging from the two-body SO

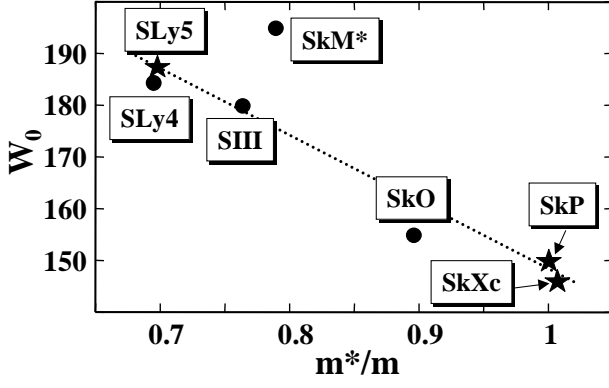


FIG. 2: The isoscalar strength of the two-body spin-orbit interaction plotted as a function of the isoscalar effective mass parameter for a few popular Skyrme force parameterizations studied here including SLy4, SLy5 SkO, SkI, SkXc, SkP, and SkM*. Stars mark the Skyrme forces having non-zero tensor terms.

interaction $W_0 = -2C_0^{\nabla J}$ appears to be almost perfectly linearly correlated with the effective mass m^* parameter as shown in Fig. 2. Large values of W_0 which characterize low- m^* forces tend to reduce the $d_{3/2}$ - $f_{7/2}$ splitting thus compensating the m^* -scaling effect on the $N=Z=20$ magic gap. As shown in Ref. [20] a similar cancellation takes place for the $p_{1/2}$ - $d_{5/2}$ and $f_{5/2}$ - $g_{9/2}$ splittings in the $A=16$ and $A=80$ mass regions, respectively. For these splittings the schematic Nilsson model indicates an indisputable dominance of the SO term over the surface (or, more precisely, the $\sim \ell^2$) contribution. On the other hand, for the $p_{1/2}$ - $g_{9/2}$ splitting in the $A=80$ mass region, the SO and the ℓ^2 contributions are predicted to be similar. For this particular case also the self-consistent SHF calculations provide results which are qualitatively different than in the previous cases indicating a more complex dependence.

The *implicit* mass scaling of the two-body Skyrme spin-orbit strength has unexpected and serious consequences: Within a single theoretical framework two conflicting scalings are present. Indeed, particle-hole excitations associated with the spin-orbit partners such as $f_{7/2} - f_{5/2}$ scale directly with W_0 . At the same time the $f_{7/2} - d_{3/2}$ *ph* excitations scale according to the $W_0^* \equiv \frac{m^*}{m} W_0$ as shown in Fig. 3. At first glance this puzzling situation seem to have no satisfactory and unique solution within the conventional Skyrme EDF. Although a reduction in W_0 (see open symbols in Fig. 3) clearly improves the agreement to the data it can hardly be accepted as a reasonable solution. Indeed, the figure indicates that the empirical $\Delta e(f_{7/2} - f_{5/2})$ splitting (experimental data are marked by thick horizontal lines in Fig. 3) is reached first by reducing W_0 strength in parameterizations characterized by large- m^* values. In contrast, agreement to the empirical $\Delta e(f_{7/2} - d_{3/2})$ splitting is obtained after reducing the W_0 strength in low- m^* parameterizations. Therefore, a conventional theory can

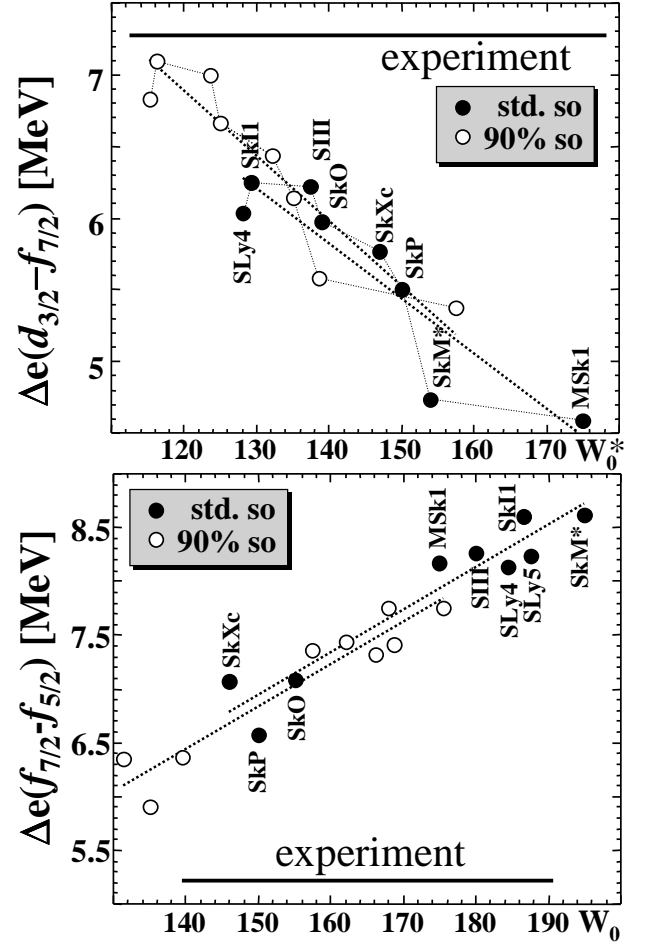


FIG. 3: Upper part shows the calculated energy splitting between $\nu f_{7/2} - \nu d_{3/2}$ single-particle states versus W_0^* calculated using different Skyrme forces. The lower part shows the $\nu f_{7/2} - \nu f_{5/2}$ spin-orbit splitting versus W_0 calculated using the same set of the Skyrme forces. Black (open) dots mark results obtained using standard (10% reduced) strength of the two-body spin-orbit interaction, respectively. The figure clearly demonstrates the presence of two conflicting scalings within the Skyrme model. See text for further details.

not reproduce simultaneously both empirical values. To state it differently: the standard set of Skyrme forces appear to be incomplete when confronted to experimental data.

Fig. 3 suggests that the simultaneous agreement for both $\Delta e(f_{7/2} - d_{3/2})$ and $\Delta e(f_{7/2} - f_{5/2})$ splittings calls for parameterizations having large m^* and drastically reduced W_0 . Drastic reduction of W_0 will spoil, however, the relatively good agreement for our high-spin observable ΔE , see Fig. 1. Hence a compensation mechanism is required. This mechanism exist, it is not new [21, 22] and it is provided by a tensor component. However, until very recently, there has been little need to invoke the *strong* tensor interaction in EDF's, see [23, 24, 25, 26, 27, 28, 29]. In our re-

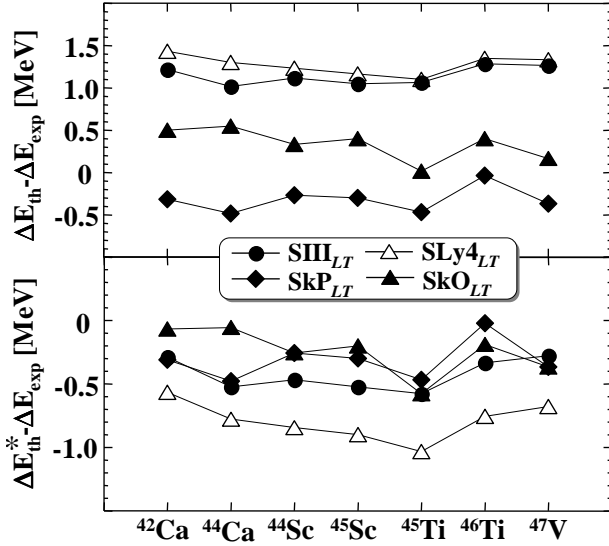


FIG. 4: The energy difference of theoretical and empirical $\Delta E_{th} - \Delta E_{exp}$ energy splittings given by Eq. (4). Upper part shows the results obtained using SLy4_{LT}, SkP_{LT}, SIII_{LT}, and SkO_{LT} parameterizations with modified spin fields and the two-body SO and tensor strengths readjusted to the empirical $\nu f_{7/2} - \nu f_{5/2}$ splittings, see table I. Lower part shows the differences $\Delta E_{th}^* - \Delta E_{exp}$ between the isoscalar effective mass scaled theoretical splitting $\Delta E_{th}^* = \frac{m^*}{m} \Delta E_{th}$ and the experimental value. See text for further details.

cent contribution [30] we have shown that the tensor interaction can be rather unambiguously fitted using the $f_{7/2} - f_{5/2}$ spin-orbit splittings in three key nuclei including: the isoscalar spin-saturated ^{40}Ca nucleus, the isoscalar spin-unsaturated ^{56}Ni nucleus, and the isovector spin-unsaturated ^{48}Ca nucleus. Unlike in the other studies cited above our work firmly revealed the need for a simultaneous drastic reduction of the two-body SO strength. Such a procedure definitely changes the philosophy behind conventional fitting strategies by shifting the attention from mass dominated gross features to procedures including carefully selected single-particle states which are used to adjust specific coupling constants in the functional.

We are now in a position to verify the consistency of our new fitting strategy using high spin terminating states. We have therefore repeated the calculations for the energy differences ΔE of Eq. (4) but using parameterizations SIII_{LT}, SkO_{LT}, SLy4_{LT}, SkP_{LT}, and SkXc_{LT}. Subscript *LT* indicates that these parameterizations have: (i) time-odd spin-fields readjusted to empirical Landau parameters and (ii) modified tensor and two-body SO strengths. New values of the tensor and the two-body SO functional coupling constants are collected in Tab. I. All other coupling constants of these parameterizations are kept to their original values.

The results of our calculations are depicted in the upper part of Fig. 4. It is interesting to observe that all large- m^* parameterizations including SkO_{LT} ($\frac{m^*}{m} \sim 0.9$)

Skyrme force	$C_0^{\nabla J}$ [MeV fm ⁵]	$C_1^{\nabla J}/C_0^{\nabla J}$	C_0^J [MeV fm ⁵]	C_1^J [MeV fm ⁵]
SkP _T	-60.0	1/3	-38.6	-61.7
SLy4 _T	-60.0	1/3	-45.0	-60.0
SIII _T	-57.6	1/3	-50.6	-64.5
SkO _T	-61.8	-1.3	-33.1	-91.6
SkXc _T	-54.0	0	-43.0	-65.2

TABLE I: Spin-orbit $C^{\nabla J}$ and tensor isoscalar C_0^J and isovector C_1^J functional coupling constants adopted for different parameterizations. These modified parameterizations are subsequently used in the calculations presented in Fig. 4.

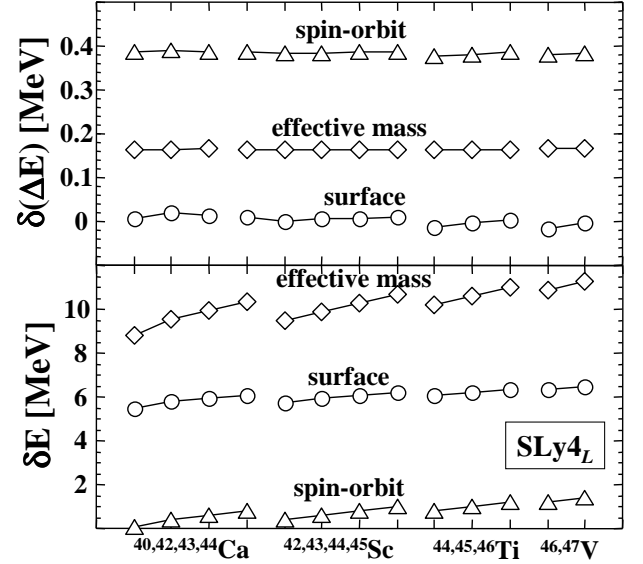


FIG. 5: The change in ΔE (upper part) and in the binding energy $E([f_{7/2}^n]_{I_{max}})$ (lower part) caused by 5% variations in $C^{\Delta\rho}$ (surface), C^τ (effective mass), and $C^{\nabla J}$ (spin-orbit) coupling constants in the Skyrme functional.

and SkP_{LT} ($\frac{m^*}{m} \sim 1.0$) are giving satisfactory agreement to the data. In the particular case of the SkXc_{LT} ($\frac{m^*}{m} \sim 1.0$) force (not shown in the figure) the mean deviation from the data equals to 33 keV only! At the same time low- m^* parameterizations including SLy4_{LT} ($\frac{m^*}{m} \sim 0.7$) and SIII_{LT} ($\frac{m^*}{m} \sim 0.8$) strongly overestimate the data. This result clearly follows the conventional wisdom related to the m^* -scaling of the s.p. level density. To visualize this even better we have rescaled the theoretical energy difference by the effective mass $\Delta E_{th}^* \equiv \frac{m^*}{m} \Delta E_{th}$ and have plotted the difference $\Delta E_{th}^* - \Delta E_{exp}$ in the lower panel of Fig. 4. Three out of four curves depicted in this figure follow closely each other and the experiment. The curve representing the SLy4_{LT} is slightly below the trend, indicating too small a reduction of the two-body SO strength (by 35%) done in Ref. [30]. The quantity ΔE can therefore be used for further fine tuning of the SO strength and indeed, a reduction of the SO strength by 40% shifts the SLy4 curve by 250 keV up as expected.

One has to remember however, that the entire effective mass scaling concept in finite nuclei is only an idealization. Last but not least let us observe that all curves shown in Fig. 4 do not reveal any clear isotopic and/or isotonic dependence, in contrast to the previous calculations presented in Fig. 1. This indicates a clear improvement of the isovector channel due to the presence of a strong isovector tensor component in the functional.

In summary, we have investigated the impact of the fitting procedures and the datasets used to fit the Skyrme energy density functionals with respect to their spectroscopic properties. We have demonstrated that the use of parameterizations fitted to reproduce bulk nuclear data in the thermodynamic limit and to binding energies of selected double-magic finite nuclei to analyze spectroscopic data may lead to rather poor results. This is due to an implicit internal m^* -scaling of, in particular, the two-body SO strength which is a mere consequence of the fitting procedure. We have further demonstrated that conventional Skyrme forces having the two-body SO strength and tensor coupling constants fitted directly to the empirical s.p. $\nu f_{7/2} - \nu f_{5/2}$ SO splittings behave according to the expected m^* -scaling law for particle-hole excitations. The present study seems to confirm the common expectation that effective interactions with large effective mass have a superior performance for calculations of spectroscopic data. It sends however a clear message that this conclusion is strongly dependent on the fitting process for effective forces. Involving a larger set of single particle data, in particular selected high spin terminating states reveal the need for a considerable reduction of the conventional two-body spin-orbit term and at the same

time the requirement for a strong tensor term introduced in Ref. [30].

This work was supported in part by the Polish Ministry of Science and the Swedish Research Council.

I. APPENDIX

In order to demonstrate the hierarchy of various contributions to the observable (4) in $A \sim 44$ mass region we have performed additional calculations using the Skyrme EDF (2)-(3). The results are depicted in Fig. 5. The upper part of the figure shows relative changes $\delta(\Delta E)$ in the energy differences ΔE caused by $\pm 5\%$ changes in $C^{\Delta\rho}$ (surface), $C^\tau (= -C^j)$ (effective mass), and $C^{\nabla J} (= C^{\nabla j})$ (spin-orbit) coupling constants with respect to their original values. The lower part illustrates relative changes in the total binding energy $\delta E([f_{7/2}^n]_{I_{max}})$ of the aligned state $[f_{7/2}^n]_{I_{max}}$ caused by these variations in the coupling constants. This figure clearly shows that the hierarchy established in Ref. [4] on the basis of the schematic Nilsen model is correct. The leading contribution to $\delta(\Delta E)$ is indeed the spin-orbit term. The contribution coming from the effective mass term is circa 2.5 times smaller and is clearly non-perturbative as it impacts binding energies by ~ 10 MeV. In the same spirit we have also investigated the influence of $\pm 1\%$ variations in the bulk energy parameter C^ρ on both ΔE and $E([f_{7/2}^n]_{I_{max}})$. These tiny variations in C^ρ impact binding energies by ~ 15 MeV and, at the same time, affect ΔE only by $\sim \pm 30$ keV.

-
- [1] W. Satuła and R. Wyss, Rep. Prog. Phys. **68**, 131 (2005).
 - [2] E. Chabanat, *et al.*, Nucl. Phys. **A627** (1997) 710; **A635** (1998) 231.
 - [3] J.P. Jeukenne, A. Lejeunne, and C. Mahaux, Phys. Rev. **C25**, 83 (1976).
 - [4] H. Zdunick W. Satuła and R. Wyss, Phys. Rev. **C71**, 024305 (2005).
 - [5] Y.M. Engel *et al.*, Nucl. Phys. **A249**, 215 (1975).
 - [6] M. Bender, P.-H. Heenen, and P.-G. Reinhard, Rev. Mod. Phys. **75**, 121 (2003).
 - [7] E. Perlińska *et al.*, Phys. Rev. **C69**, 014316 (2004).
 - [8] J. Dobaczewski *et al.*, Comput. Phys. Comm. **158** (2004) 158; HFODD User's Guide nucl-th/0501008.
 - [9] M. Beiner *et al.*, Nucl. Phys. **A238**, 29 (1975).
 - [10] J. Bartel *et al.*, Nucl. Phys. **A386**, 79 (1982).
 - [11] B.A. Brown, Phys. Rev. **C58** (1998) 220.
 - [12] F. Tondeur *et al.*, Phys. Rev. **C62**, 024308 (2000).
 - [13] J. Dobaczewski, H. Flocard, and J. Treiner, Nucl. Phys. **A422** (1984) 103.
 - [14] P.-G. Reinhard *et al.*, Phys. Rev. **C60**, 014316 (1999).
 - [15] M. Bender *et al.*, Phys. Rev. **C65**, 054322 (2002).
 - [16] W. Satuła, R. Wyss, and M. Rafalski, Phys. Rev. **C74**, 011301(R) (2006).
 - [17] G. Stoitchewa *et al.*, Phys. Rev. **C73**, 061304(R) (2006).
 - [18] M. Zalewski *et al.*, Phys. Rev. **C75**, 054306 (2007).
 - [19] H. Zdunick *et al.*, Phys. Rev. **C76**, 044304 (2007).
 - [20] M. Zalewski and W. Satuła, Int. J. Mod. Phys. **E16**, 386 (2007).
 - [21] H. Flocard, Thesis 1975, Orsay, Serie A, No 1543.
 - [22] Fl. Stancu, D.M. Brink, and H. Flocard, Phys. Lett. **B68**, 108 (1977).
 - [23] T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005).
 - [24] J. Dobaczewski, in Proceedings of the *Third ANL/MSU/INT/JINA RIA Theory Workshop: Opportunities with Exotic Beams*, Argonne, IL, April 4-7, 2006, eds. T. Duguet, H. Esbensen, K. M. Nollet, and C. D. Roberts (World Scientific, Singapore, 2007), p. 152; arXiv:nucl-th/0604043.
 - [25] B.A. Brown *et al.*, Phys. Rev. **C74**, 061303(R) (2006).
 - [26] T. Lesinski *et al.*, Phys. Rev. **C76**, 014312 (2007).
 - [27] G. Colo *et al.*, Phys. Lett. **B646**, 227 (2007).
 - [28] M. Grasso *et al.*, Phys. Rev. **C76**, 044319 (2007).
 - [29] T. Otsuka *et al.*, Phys. Rev. Lett. **87**, 082502 (2001).
 - [30] M. Zalewski *et al.*, arXiv:nucl-th/0801.0924.